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Vision Research 39 (1999) 3241–3252

Vision Research

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Flicker and the efficiency of cues for capturing attention

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Received 29 May 1998; received in revised form 2 December 1998

Abstract

In this paper, we present new experimental results which speak of the topic of temporal properties of processes underlying the selection of spatial location. We used the double motion induction paradigm to assess the strength of the selective effects. Prior exposure of an area to flicker, decreased the effectiveness of a cueing spot presented later at that location. This effect lasted for at least 1.5 s. In further experiments, it was found that both static and flickering cues, with time, lose their effectiveness to facilitate processing. While the static cueing decays quickly to very low effectiveness, flicker cueing decays to a level of effectiveness which can be maintained for a long time. Thus with time two flickering cues presented with a temporal offset become equivalent to each other, but remain more effective than a static cue. We conclude that mechanisms coding temporal change determine cue effectiveness for capturing attention. Simple exponential decay functions with different temporal constants and different lower asymptotes can describe these effects.

Keywords: Attentional capture; Selection; Flicker; Transient; Motion induction

1. Introduction

The abrupt onset of a stimulus is an event which has special significance for the visual system. It is known to capture attention (Yantis & Jonides, 1984; Yantis, 1993; Yantis & Hillstrom, 1994), and it may also provide one form of the bottom-up facilitation in the selection of a spatial location. We have shown that it can drive the perceived motion in the motion induction illusion in a pre-attentive way (Faubert & von Grünau, 1995; Faubert, 1996; von Grünau, Dubé & Kwas, 1996b). It is not clear, however, whether the pre-attentive effect of an isolated cue is actually carried by early and local sensory signals or whether it is due rather to its saliency, i.e. to the fact that it defines a contrast with respect to its immediate surroundings (von Grünau & Iordanova, 1997; Zanker, 1997). In this context, Nakayama and Mackeben (1989) have argued that transient attention is not carried by early sensory signals, based on cueing experiments in a visual search paradigm. They found that repeating the abrupt onset by flickering the cue did not prolong the facilitation effect. Facilitation also occurred when there was no abrupt cue onset, although its latency was increased. The longer time may have been necessary for a more elaborate saliency operation when the decoy cues were turned off (compare to the pop-out effect in von Grünau et al. (1996b)).

In the present paper we report experiments which examine the nature of the effect of flicker on attention captured by cue onset. First, we show that prior adaptation to flicker of an area weakens the effectiveness of a subsequent cue to capture attention. We then demonstrate that flicker of the cue itself increases a cue's effectiveness, as compared to a static cue, and measure the temporal decay of this effect. All experiments utilize the motion induction effect (MI) (Faubert & von Grünau, 1992) which has also been referred to as the line motion illusion (Hikosaka, Miyauchi & Shimojo, 1991). In the original demonstration of the line motion effect, a spot was presented, followed after a short time delay by a line or bar, abutting the spot at one of its ends. The spot remained present throughout the presentation of the bar, and although the bar was presented as a complete unit, it appeared to be growing out of

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0042-6989/99/$ - see front matter
PII: S0042-6989(99)00014-0

and away from the spot (see Fig. 1). When the bar was presented between two spots (split priming or double MI effect), with the two spots appearing simultaneously followed by the bar, the perception was that of a collision in the center of the bar (von Grünau & Faubert, 1992; Faubert & von Grünau, 1995). When a time delay (stimulus onset asynchrony, SOA) was introduced between the presentation of the two spots, the collision was perceived to occur closer to the first spot, rather than in the center of the bar, and increasingly so as SOA increased (Faubert & von Grünau, 1995). It must be emphasized that, when there is a space between spot and bar, the motion still occurs only within the bar and not in the space between the spot and the bar, as it would in typical stroboscopic motion situations (Wertheimer, 1912).

This latter observation is one important factor that distinguishes the MI effect from stroboscopic apparent motion. Inspite of this, it has been argued that MI and stroboscopic apparent motion could be subserved by the same mechanism (Kawahara, Yokosawa, Nishida & Sato, 1996; Downing & Treisman, 1997; Zanker, 1997). We and others, however, have provided much evidence and reasoning for a gradient model for MI which can account for MI effects involving directed attention, captured attention or no attention in a parsimonious way (von Grünau, Racette & Kwas, 1996a; von Grünau et al., 1996b; Schmidt & Klein, 1997; Shimojo, Miyauchi & Hikosaka, 1997; von Grünau & Iordanova, 1997; Schmidt, Fisher & Pylyshyn, 1998; Steinman & Steinman, 1998). While the MI effect is best accounted for by the operation of both bottom-up and top-down processes, the double MI effect in particular, as used in the present experiments, has been found to be primarily a reflection of early bottom-up processes, since it is affected by low-level stimulus attributes, eye of presentation and stimulus geometry (Faubert & von Grünau, 1995; von Grünau, Saikali & Faubert, 1995).

2. Experiment 1: prior flicker adaptation

If bottom-up motion induction effects involve early sensory signals it is most likely that these signals are those carried by the transient or magno-cellular (M) system. A fast transient preparatory signal has been suggested previously (Breitmeyer & Ganz, 1976; Lennie, 1980), and has also been implicated recently in the motion induction effect (Steinman, Steinman & Lehmkuhle, 1997). It has been shown that cues which would stimulate neurons of the M pathway especially well, were most effective in inducing this illusion. To further examine whether transient mechanisms are involved in generating the motion induction illusion, this experiment studies the effect of weakening transient neurons on the effectiveness of a cue. We attempted to adapt the transient system by a luminance flicker in the area where one of the two spots of a double MI paradigm would appear. This adaptation was expected to weaken particularly the transient signals that could arise from this location, and thus shift the usually perceived central collision of motion in the bar toward the location of the adapted spot (see Fig. 1).

2.1. Methods

2.1.1. Subjects

Six observers, four of them naive as to the purpose of the experiment took part. They had normal or corrected-to-normal vision, as assessed by spatial and temporal sensitivity measures.

2.1.2. Apparatus

The experiment was conducted with a Macintosh IIci computer, with stimuli being displayed on an Apple High Resolution RGB monitor. Subjects viewed the display from a distance of 57 cm and used a chin and forehead rest for stabilization. The stimuli were created, and the experiment was controlled by the Pixx software, developed in our lab.

2.1.3. Stimuli

The motion induction display consisted of two spots with sides of 0.3°, presented on each side of a bar (0.3° high and 4.5°long). There was a gap of 0.6° between the edges of the spots and the bar. The flickering field was

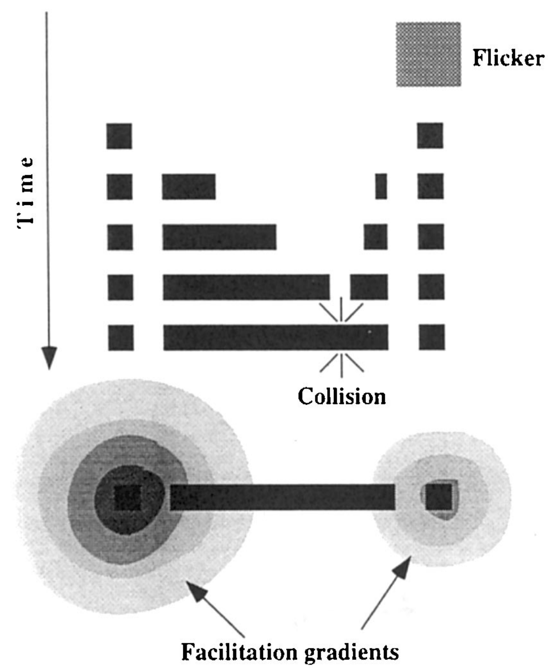

Fig. 1. Expected perception with flicker field for the right spot. Collision is shifted toward the adapted location. The facilitation gradient is smaller and weaker. Note that the bar is actually presented in its entirety at one time, but perceived to grow away from the spots.

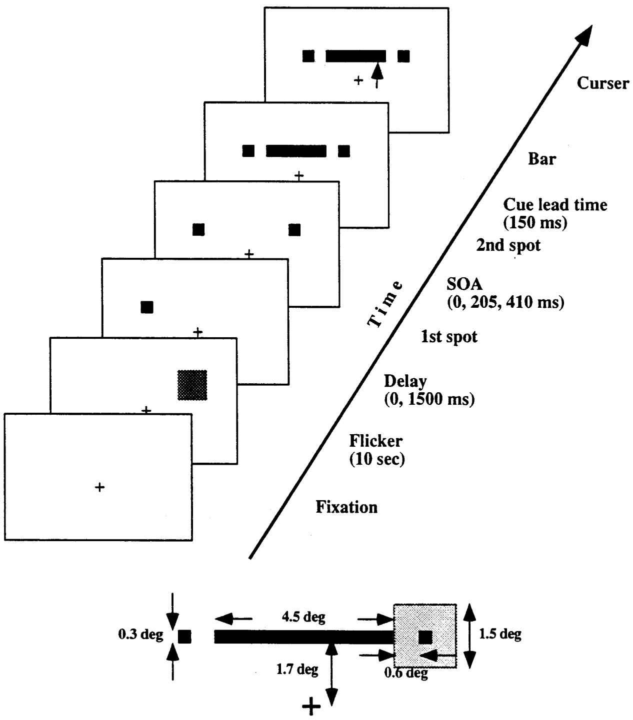

Fig. 2. Presentation sequence of an experimental trial and stimulus dimensions for Experiment 1. In this case, flicker adaptation was at the location of the second spot.

presented at the location of one of the spots and subtended 1.5° on each side. A fixation cross was located in the center of and 1.7° below the bar. The spots and the bar appeared white (82.07 cd/m^2) on a grey (32.63 cd/m^2) background (43% Michelson contrast). The flickering field fluctuated in luminance between 0.17 and 66.18 cd/m^2 in a square-wave fashion (mean luminance 33.26 cd/m^2; 50% duty cycle) at three different flicker rates: 3.3, 6.7, and 22.2 Hz.

2.1.4. Procedure

The experiment consisted of control and experimental trials. The experimental trials differed from the controls by the presence of a flickering field during the adaptation period (see Fig. 2). A trial consisted of the presentation of the fixation point, which remained throughout. After 0.5 s, the flickering field appeared either in the left or the right position (except for the control trials, where the background remained). The flickering field remained for 10 s, and was then replaced immediately or after a delay of 1500 ms by the motion induction display. The two spots near each end of the bar were presented simultaneously or with SOAs of 205 or 410 ms. The bar was then presented after a fixed cue lead time of 150 ms, and the display disappeared after the response was made. There were 72 experimental and 12 control conditions. The adaptation field could appear equally often on the left and on the right side, and this could be combined with either the 1st or 2nd spot. There were then three flicker frequencies (3.3, 6.7, 22.2 Hz), two delays (0, 1500 ms), and three SOAs (0, 205, 410 ms), adding up to 72 conditions. The control conditions comprised three SOAs, two delays, and 1st spot left or right. Each condition was repeated five times to make 420 trials in all, which were run in two sessions.

2.1.5. Task

The observers' task was to fixate the fixation cross throughout each trial and to position a curser, which appeared on the screen shortly after the bar near the fixation point. The curser was to be aligned with the perceived position of the collision point of the movement within the bar. These values were recorded by the computer as numbers between -1.00 and $+1.00$, whereby 0.00 denotes collision in the center.

2.2. Results and discussion

Since the position of the presentation of the flickering field did not affect the results, we combined those trials and present the results as if the 1st spot had always appeared on the right. We also present the results for the different values of SOA separately and collapse over flicker at 1st or 2nd spot. Separate ANOVAs were computed for each SOA. When the SOA between the two spots was zero (see Fig. 3A), the control trials indicated that collision was perceived almost exactly in the center of the bar on average. This is shown on the top of the figure. The change of the collision point after flicker adaptation is shown below by the horizontal bar graphs, aligned to the control collision point. In all cases, the new collision point was closer to the position of the 1st spot, where the adaptation field was located. This means that the effectiveness of this spot was weakened so that motion away from the non-adapted spot was stronger. This effect was most pronounced when the spots were presented immediately after the flicker and had decayed significantly after 1500 ms [$F(1, 5) = 14.25$; $P = 0.013$]. It also appeared strongest for the flicker frequency of 6.7 Hz, but this effect was not significant [$F(2, 10)$; $P = 0.12$].

When the SOA was 205 ms (see Fig. 3B), the control trials showed a collision point shifted about 3/4 of the way toward the position of the 1st spot, indicating that the 2nd spot was largely determining the perceived motion (Faubert & von Grünau, 1995). The effects of the various flicker conditions are again shown below, with the zero point aligned with the control collision point. When the flicker field was located where the 2nd spot appeared, the collision point was shifted further toward this spot as compared to the control. This was true for all flicker frequencies and strongest when there was no delay [$F(1, 5) = 10.98$; $P = 0.02$]. The effect was largest for the lowest flicker frequency [$F(2, 10) = 8.87$;

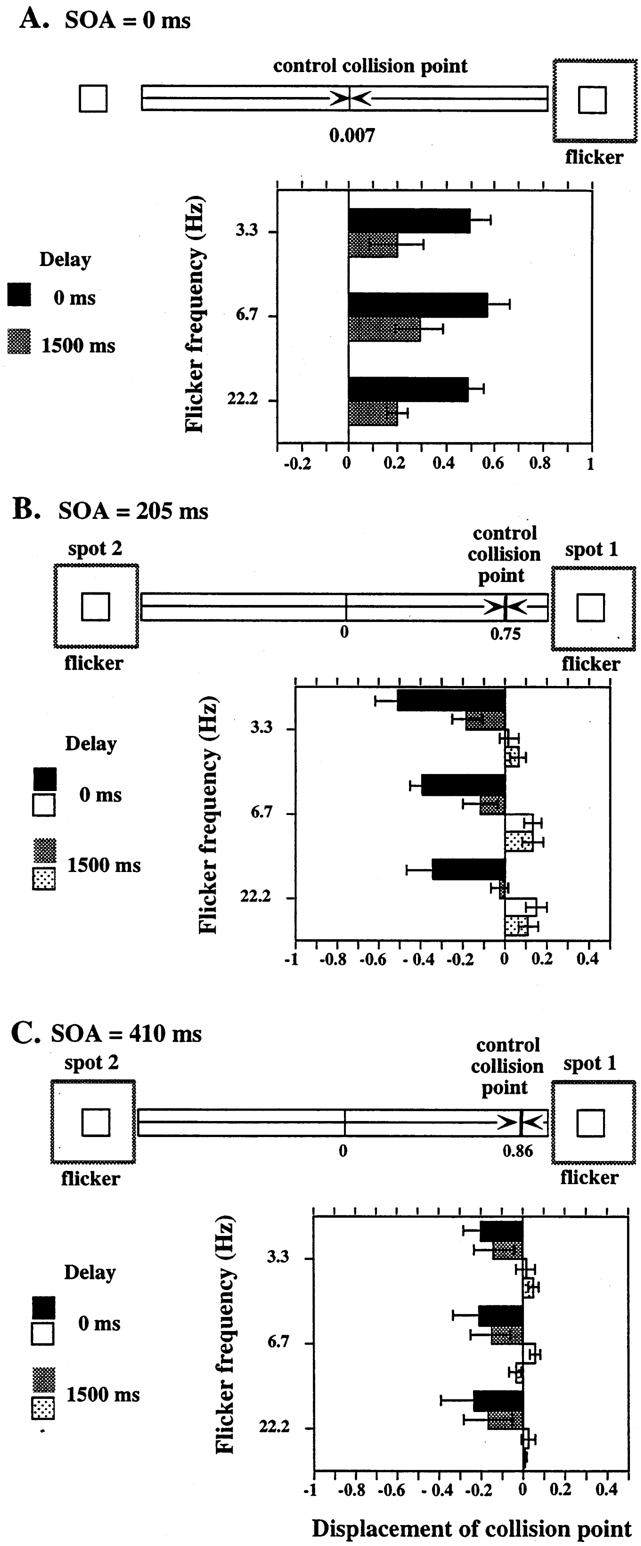

Fig. 3. Average displacement ($1.00 = 2.2°$) of the collision point from the control position after flicker adaptation. (A) SOA = 0: Results are shown for different flicker frequencies and delays between flicker and the two spots. (B) SOA = 205 ms and (C) SOA = 410 ms: Top two bars at each flicker frequency are for flicker at location of spot 2, for both delays. Bottom two bars are for flicker at location of spot 1, for both delays. Displacement toward the cue with prior flicker exposure indicates reduced effectiveness of this cue.

$P = 0.006$]. When the flicker field was in the location of the 1st spot, the collision point was shifted even further toward the position of this spot, but the size of the effect was much smaller [$F(1, 5) = 14.96$; $P = 0.012$]. Again the effect appeared in a similar way for all flicker frequencies, but the effects for delay and flicker frequency were not significant, since ceiling was almost reached. In all cases, however, these results are consistent with a weakening of the influence of the spot that is presented at the location of the flickering field.

The results were in principle very similar when the SOA was 410 ms (see Fig. 3C). In the control trials, the collision point was pushed even further toward the 1st spot. Flicker adapting the area of the 2nd spot brought the collision point more toward the center, and adaptation of the 1st spot location had little additional effect (since the end of the bar was almost reached in the control trials). Though the trends were similar to those for an SOA of 205 ms, none of the effects were statistically significant ($P = 0.05$).

This experiment has shown that the effectiveness of the cues which determine the illusory motion direction in the motion induction effect depends crucially on mechanisms that are weakened by prior adaptation to luminance flicker. The effect is maximal immediately after adaptation, and has decayed to less than 50% after 1500 ms. The fast decay of the adaptation effect is also apparent from the fact that the shift of the collision point becomes smaller with increasing SOA, which delays the onset of the 2nd spot. Nonetheless, both the 1st and the 2nd spot can be influenced by flicker adaptation, and the effect on the 2nd spot appears stronger, possibly since it is the dominant cue. All flicker frequencies used here had about equivalent effects.

It is possible that the flickering field might itself function as a cue capturing attention. It consists of many abrupt onsets which have been shown to attract attention (Yantis, 1993; Dougherty, Smith, Verardo & Mayer, 1996). On the other hand, Nakayama and Mackeben (1989) have reported that the transient component of attention cannot be prolonged by flickering the cue. Thus a stimulus flickering for 10 s is not expected to function as an effective cue. In the subsequent experiments, we show that a flickering cue loses some of its effectiveness, but retains enough even after an appreciable time to dominate a static cue (see Section 4).

Even with the longest SOA (410 ms), the collision point was shifted only about 86% of the way toward the first spot without flicker adaptation. One might expect that after 560 ms (SOA + CLT) the strength of the 1st spot to capture attention to be reduced to zero, since attention should have shifted completely to the 2nd spot. This incomplete shift has been reported before for even longer times (Faubert & von Grünau,

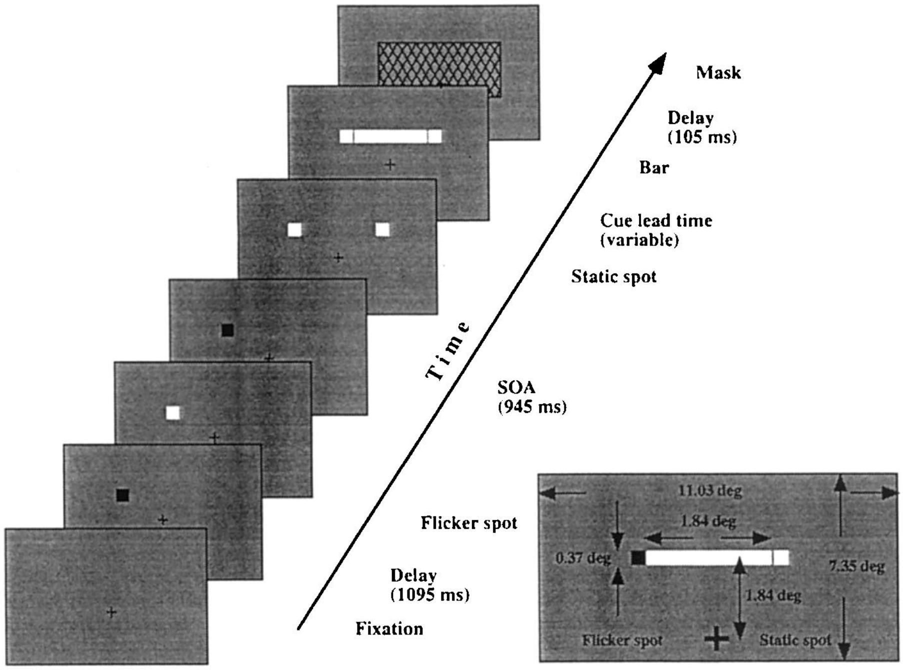

Fig. 4. Presentation sequence and stimulus dimensions for Experiment 2.

1995). It can also be seen in the results of the present Experiment 4, where the effectiveness of a static cue is still present after CLTs of 500 or 600 ms (Fig. 7). This may reflect the concept of split priming (Faubert & von Grünau, 1995), where it is assumed that the 1st cue does not have to loose its effectiveness before the 2nd cue can be effective. It may also be related to the involvement of low-level non-attentional facilitation in double MI (von Grünau & Iordanova, 1997).

We conclude that prolonged inspection of a flickering field has adapted those mechanisms that are sensitive to rapid luminance change. It is the transient M system which is most sensitive to luminance change, especially fast change, and so we conjecture that signals initiated by the presentation of the priming spot and carried by M-type neurons are necessary for the motion induction illusion. According to the facilitation model described in von Grünau and Iordanova (1997), the gradient of facilitation which is set up after adaptation must be much flatter than when there is no adaptation. The speed-up of the corresponding end of the bar is accordingly less than for the other end where the spot is processed by an unadapted mechanism. It follows that the latter becomes dominant in determining motion direction.

3. Experiments 2–5: Flickering versus static cues

In Experiment 1, we attempted to influence the signal transmission properties for the priming spot prior to the presentation of the spot and thus change its effectiveness. We will now compare the effectiveness of the two spots directly by varying their temporal properties in a double motion induction paradigm. Previous evidence regarding the effectiveness of stimuli changing over time does suggest that abrupt onsets are highly effective in capturing attention (Yantis, 1993; Yantis & Hillstrom, 1994), while offsets are not as good (Jonides & Yantis, 1988). In visual search, high frequency flickering targets also seem to capture attention better than low frequency targets (Dougherty et al., 1996). On the other hand, flickering a cue is not effective in renewing the transient component of focal attention at a location (Nakayama & Mackeben, 1989). In double motion induction both cues are turned on abruptly, and this leads to equal effectiveness and central collision. But the effectiveness declines over time, and when one cue is presented prior to the other, the second cue comes to dominate the illusory motion with a sufficiently long SOA (Faubert & von Grünau, 1995).

In a previous experiment (von Grünau, Iordanova & Rajska, 1997) we presented both spots simultaneously, but one spot (static cue) came on abruptly and remained on at maximum luminance and contrast. The other spot (flickering cue) changed from black (like the background) to white (like the static spot and the bar) for a variable number of cycles and with variable speed. It was found that the static cue was dominant initially (perhaps due to the graded onset of the flickering cue). After a short time, however, the flickering cue became dominant. Temporal change seemed to be more effective than high intensity. The results suggested that a static cue's effectiveness decays rapidly with time, while that of a flickering cue remains unaffected or decays much more slowly. In the following experiments, this idea was tested further by putting static and flickering cues in competition for the control over the direction of illusory motion in MI.

3.1. General methods for Experiments 2–5

3.1.1. Apparatus

The experiments were conducted with PowerMac computers, with stimuli being displayed on Apple High Resolution RGB monitors. Subjects viewed the displays from a distance of 57 cm and used a chin and forehead rest for stabilization. The stimuli were created, and the experiment was controlled by the Pixx software.

3.1.2. Stimuli

The display (shown in Fig. 4 for Experiment 2) consisted of two horizontally arranged spots (squares with sides of 10 pixels or 0.37°). They were separated center-to-center by 60 pixels (2.2°). A horizontal bar ($0.37 \times 1.84°$ or 10×50 pixels; maximum luminance of 82 cd/m^2) was presented between the spots. Finally a mask stimulus ($7.35 \times 11.03°$ rectangle filled with a crosshatched pattern) followed. The background was always at medium luminance (41 cd/m^2). The spots could be static or flickering. The static spot was abruptly turned on and remained at the maximum luminance of 82 cd/m^2. The flickering spot varied in luminance in a squarewave fashion between minimum (0.17 cd/m^2) and maximum (82 cd/m^2) luminance every 45 ms. It always started with the minimum and ended with the maximum luminance. The flickering spot was always bright when the bar was presented. At that point, both spots and the bar had the same luminance, which they kept until they were replaced by the mask. A fixation cross ($0.44 \times 0.44°$) was present in the center and 1.84° below the stimuli throughout the trial.

3.1.3. Task

The subject's task was to fixate the fixation cross for the whole trial and to indicate the direction of the perceived motion in the bar, left or right, by pressing an appropriate key. It was a forced-choice response, and subjects were told to guess when necessary.

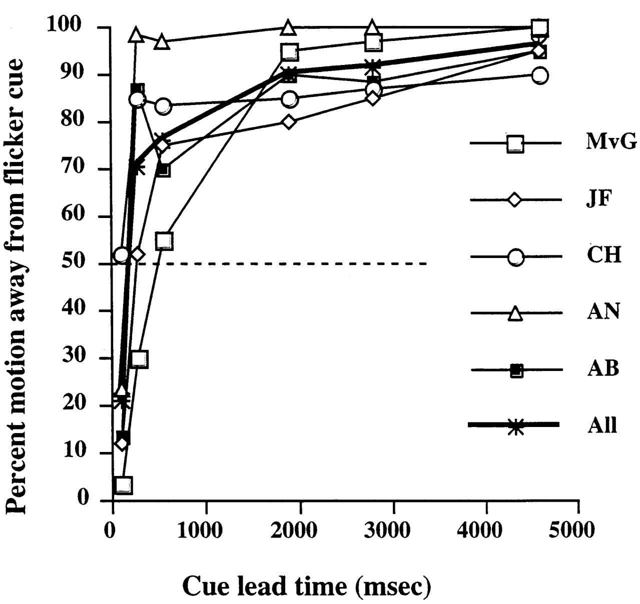

Fig. 5. Results for Experiment 2. The relative dominance of the flickering cue increases with increasing presentation time of the static cue (cue lead time). Results for individual subjects and average.

3.2. Experiment 2

In Experiment 2, a flickering cue was followed by a static cue after a certain delay (stimulus onset asynchrony, SOA) and a test bar was presented with variable delays (cue lead times, CLT) after the onset of the static cue. If the effectiveness of the flickering cue remained more or less unchanged, this cue would be expected to be dominant for all CLT. If, on the other hand, the flickering cue's effectiveness decayed as well but less rapidly, one would expect the static cue to be dominant for short CLT, but the flickering cue to be dominant for longer CLT.

3.2.1. Methods

3.2.1.1. Subjects. Five observers, three of them naive as to the purpose of the experiment took part. They all had normal or corrected-to-normal vision, as assessed by spatial and temporal sensitivity measures.

3.2.1.2. Procedure. The subject initiated each trial when ready and fixating on the fixation cross. After 1095 ms, the flickering spot appeared on the screen, followed by the static spot after an SOA of 945 ms (10.5 cycles of flicker). The bar appeared after a variable CLT after the last switch to bright by the flickering spot: 90, 270, 540, 1890, 2790, and 4590 ms. The whole arrangement was replaced by the mask after 105 ms. The mask remained present until the subject responded. The experiment comprised 12 conditions (six CLT each for the static spot on the left or the right). Three sessions of ten replications of each condition (a total of 360 trials) were run for each subject.

3.2.2. Results and discussion

The results consisted of the percentage of responses indicating motion away from the flickering spot. This is graphed in Fig. 5 as a function of the CLT combined for the two arrangements (static left or right). The five subjects gave fairly consistent results. For the shortest CLT, the static cue was more efficient than the flickering cue. This quickly reversed with longer CLT so that

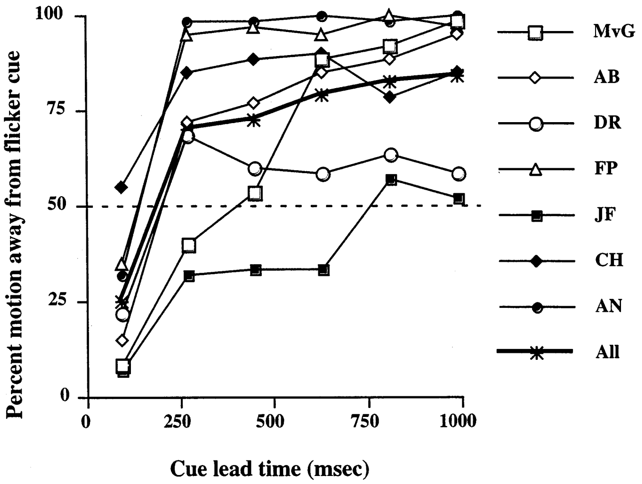

Fig. 6. Results for Experiment 3. The effectiveness of the flickering cue relative to the static cue increases with the time that both cues have been presented (cue lead time). Results for individual subjects and average.

for CLTs of 1890 ms and longer, the flickering cue was dominant in about 90% of the cases. This effect is highly significant, as shown by a one-way ANOVA [$F(5, 20) = 19.95$; $P = 0.00005$].

The fact that the static cue dominated for short CLTs and the flickering cue became more efficient for longer CLTs, suggests that the efficiency of the static cue was high at its onset and then declined quickly, whereas that of the flickering cue also decayed with time, but much more gradually. At some point the two decay functions intersect, and at that point both cues are equally effective. Here this occurred at approximately 1145 ms after onset of the flickering cue and 200 ms after onset of the static cue. The point of intersection of the two decay functions was also investigated in the next experiment.

3.3. Experiment 3

The conclusion from Experiment 2 has been that the effect of a flickering cue also decays with time, but much slower than that of a static cue. In the present experiment, the effect of the flickering cue was allowed to decay always to the same degree when the test bar was presented. As usual, the bar appeared between the flickering cue and the static cue, this time at a fixed delay after onset of the flicker cue. The static cue appeared at a variable time after onset of the flicker cue, but before the bar. We measured the SOA between onset of flicker and static cue necessary to cancel the two effects on the bar.

3.3.1. Methods

3.3.1.1. Subjects. Seven observers, five of them naive as to the purpose of the experiment took part. Five observers had also performed Experiment 2.

3.3.1.2. Procedure. The subject initiated each trial when ready and when he/she maintained good fixation on the cross. First the flickering cue appeared after a delay of 1095 ms, randomly on half the trials on the left and on the other half on the right. It was joined after a variable SOA by the static cue on the other side. The following SOA values were used: 45, 225, 405, 585, 765, and 945 ms. The bar appeared with a fixed delay after flicker cue onset of 1035 ms. Expressed in terms of CLT (i.e. the delay between the onset of the static cue and that of the bar), this results in the following values: 990, 810, 630, 450, 270, and 90 ms. The whole arrangement was replaced by the mask after 105 ms. The mask remained until the subject responded. The experiment comprised 12 conditions (six CLT each for the static spot on the left or the right). Three sessions with each 10 replications of each condition (a total of 360 trials) were run for each subject.

3.3.2. Results and discussion

The percentage of motion away from the flickering cue is graphed in Fig. 6 as a function of the CLT ($\text{CLT} = 1035 - \text{SOA}$), averaged over the two arrangements (static spot on the left or right) for all subjects and for the average. The static cue was found to be dominant only for the shortest CLT. For increasing CLT the flickering cue was increasingly dominant. There was some variability between the subjects, but all showed the same behavior. A one-way ANOVA showed that the effect of CLT was highly significant [$F(5, 30) = 24.62$; $P < 0.00005$].

The present results are very similar to those of the previous experiment and indicate that the efficiency of the two cues was equal after the presentation of 845 ms of the flickering cue and 190 ms of the static cue. These values correspond closely to those of the previous experiment and suggest again that the efficiency of a flickering cue does decay over time, but with a much longer time constant than that for a static cue.

3.4. Experiment 4

If the hypothesis developed from the results above, namely that the efficiency of a flickering cue decays slowly over time, the following can be predicted. If a flickering cue is allowed to flicker for some time and is then paired with another flickering cue in a double motion induction paradigm, its efficiency would be expected to have decayed so that the second flickering cue should be dominant. From what we have learned in the previous experiments, the second cue's dominance should not be very strong and should disappear with increasing CLT. If the second cue is static, however, we expect it to be dominant for short CLTs, but quickly give way to a strong and persisting dominance of the flickering cue. In the present experiment, we directly compared these two situations.

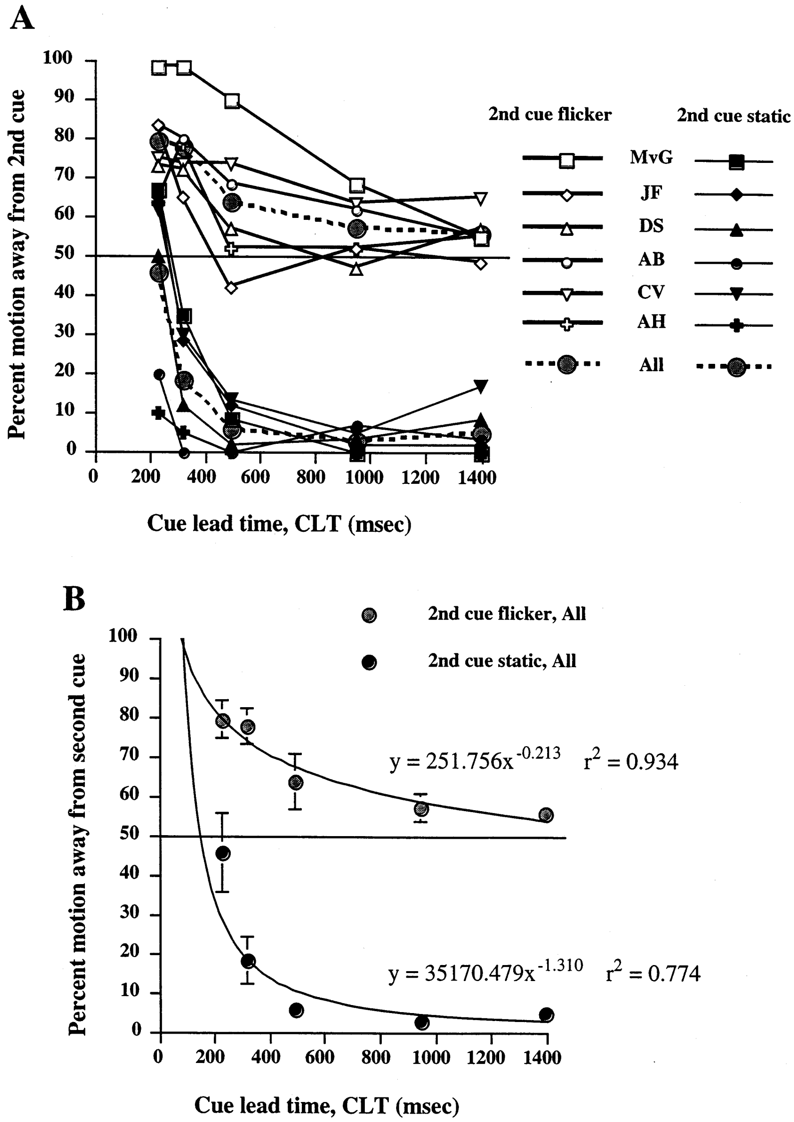

Fig. 7. Results for Experiment 4. (A) Curves for individual observers and average, when the second cue was flickering (top) or static (bottom). (B) Average data points with standard errors and best-fit power functions. These functions also represent *directly* the decay of effectiveness of a flickering cue and a static cue, respectively.

3.4.1. Methods

3.4.1.1. Subjects. Six observers, four of them naive as to the purpose of the experiment, took part. Three observers also participated in Experiments 2 and 3.

3.4.1.2. Procedure. The subject initiated each trial when ready and when he/she maintained good fixation on the cross. First the flickering cue with a cycle length of 90 ms appeared after a delay of 1095 ms, randomly on half the trials on the left and on the other half on the right. It was followed after a fixed SOA of 2250 ms by either a similar flickering spot in phase or a static spot on the other side of the bar location. After a variable CLT (225, 315, 495, 945, and 1395 ms) a bar was presented between the two spots. At that point all stimuli were bright. After another 105 ms the display was replaced by the mask which remained until the subject responded. The experiment comprised 20 conditions (five CLT each for the static and flickering second spot, both for the first spot on the left or the right). Three sessions with each ten replications of each condition (a total of 600 trials) were run for each subject.

3.4.2. Results and discussion

The percentages of motion away from the second cue (flicker or static) were compiled and averaged over the two arrangements (position of first spot). They are presented in Fig. 7A as a function of CLT for each subject and as an average. The results for a second flickering cue (upper group of curves) show that for short CLT this cue dominated the first flickering cue, but that its effectiveness declined slowly with CLT [$F(4, 20) = 11.52$; $P < 0.001$], so that the curve approached the 50% line. This indicates that after some time the two flickering cues became equivalent in their strength to determine the direction of MI in the test bar.

When the second cue was a static spot (lower group of curves), this spot again had its maximum effectiveness at the shortest CLT, but even here it was at best equivalent to the first cue which had been flickering for at least 2475 ms. For longer CLT, the static cue's effectiveness decayed rapidly [$F(4, 20) = 15.97$; $P < 0.001$], since after only a short time it could no longer affect the perceived direction of the test bar. All observers showed the same trends, but were differentially sensitive at the shortest CLT. For some observers, the static cue had lost its effectiveness almost completely already after 225 ms. For others this occurred somewhat later.

In Fig. 7B, the means are graphed with their standard errors, and the data points are fitted by decaying power functions. In both cases, the fits are quite good and demonstrate the differential decay rates for the flickering and static cue. This is also confirmed by the significant interaction in the ANOVA [$F(4, 20) = 4.95$; $P = 0.0061$].

The results of this experiment agree well with those of the previous ones. Here the differential effectiveness of flickering and static cues could be demonstrated directly. It was confirmed that a static cue is rather ineffective at maintaining selection of a spatial location. On the other hand a flickering cue can remain effective for quite some time, the limits of which we have not yet explored. Its effectiveness, however, also declines with time, but reaches assymptote at a level which remains well above zero.

3.5. Experiment 5

Finally, both ways in which we have used flicker in these experiments can be pitted against each other to see whether they constitute equivalent manipulations. The last onset of a flickering cue like in Experiment 2 before presentation of the test bar, can be considered as the onset of a cue after flicker adaptation of this location in the sense of Experiment 1. In order to compare the effectiveness of the latter event to one where the flickering area is of the same size as the cues, we presented in the present experiment two adapting flickering stimuli prior to the double MI paradigm. One of the adapting stimuli occupied a much larger area (like Experiment 1), and the second adapting stimulus maintained the same dimensions as the subsequent cues (like Experiments 2–4).

3.5.1. Methods

3.5.1.1. Subjects. Four observers, two of them naive as to the purpose of the experiment, took part. All observers had also participated in previous experiments.

3.5.1.2. Procedure. Following a pause of 1095 ms after the presentation of the fixation cross, a small (0.37° square) and a large (1.5° square) area separated horizontally were flickered in phase for 25 cycles of 90 ms (one cycle is 45 ms dark and 45 ms bright). After a variable delay during which only the fixation cross was presented, two bright spots appeared in place of the two areas near either end of the bright test bar, which was presented after a further fixed delay (CLT = 90 ms). This was followed after 105 ms by the large mask which remained until the subject responded (see Fig. 8A). The experiment comprised eight conditions [four delays (0, 900, 1800, 3600 ms), with the large area equally often on the left or on the right]. Three sessions with each ten replications of each condition (240 trials total) were run for each subject.

3.5.2. Results and discussion

In Fig. 8B the percentage of trials in which illusory motion in the test bar was away from the cue that replaced the large flickering spot is graphed as a function of the delay between the onset of flicker and the onset of the static cues. Clearly motion is predominantly away from the side with the large adapting spot for short delays. This effect disappears at a delay of about 1800 ms (20 cycles). An ANOVA shows that this decay is statistically significant [$F(3, 9) = 21.2$; $P < 0.0005$].

These results demonstrate that flickering the location of the two cues prior to their presentation is not the crucial factor here, since this was equal for both cues. The greater effectiveness of the cue at the location of the large flickering area points to the operation of another factor. One possibility is that this cue is smaller than its flickering precursor and thus constitutes also the appearance of a new object. The other cue is of the same size as its precursor and thus lacks this novelty. And new objects have been found to attract attention (Johnston, Hawley & Farnham, 1993; Yantis, 1993; Wang, Cavanagh & Green, 1994; Yantis & Gibson, 1994).

4. General discussion

In the present experiments, we examined the influence of fast temporal change on the effectiveness of stimuli that serve as cues drawing attention to a location in visual space. We showed that prior exposure of a location to luminance flicker results in a reduction of the strength of a later cue to effectively select this location. We also measured the effectiveness of a flickering cue itself as a function of time. The effectiveness of such a cue in selecting a spatial location declined with time, but remained at an asymptotic level which still rendered this flickering cue much more effective than a high-contrast static cue.

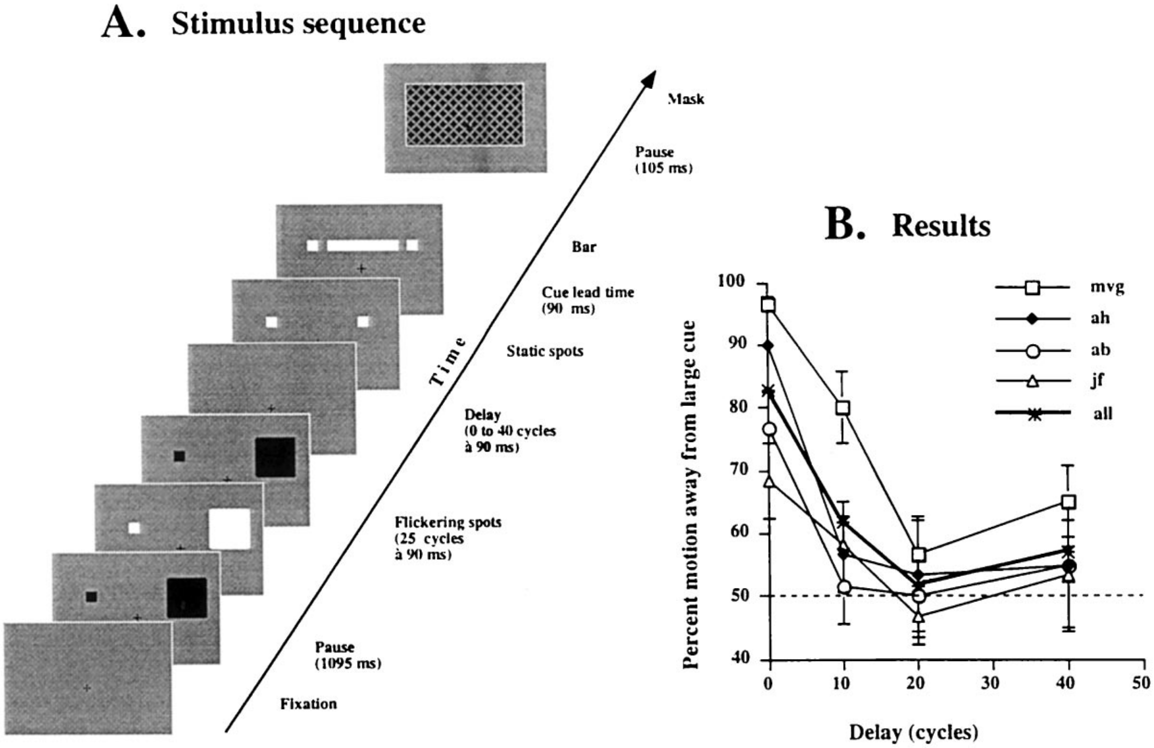

Fig. 8. Experiment in which flicker adaptation of an area (large spot) is contrasted with the prolonged flickering of a cue (small spot). (A) Stimulus sequence. (B) Results as a function of the delay between adaptation and cueing for four observers and the average.

4.1. Relationship to previous studies

It is well known that the abrupt onset of a stimulus is a very effective cue for attentional selection (Yantis & Jonides, 1984; Yantis, 1993; Yantis & Hillstrom, 1994), while stimulus offset does not have a similarly strong effect (Jonides & Yantis, 1988). In the present experiments, the flickering stimulus can be regarded as a series of onsets and offsets. Each onset should be an effective cue. We measured the strength of these onsets as a function of time or equivalently as a function of the number of repetitions. As this number increased, we found that the flickering cue became less effective. However, by comparing it directly to a static cue, which we know loses effectiveness over time (e.g. Faubert & von Grünau, 1995) it was found that the flickering cue maintains a much higher level of effectiveness. The static cue was superior in Experiment 3 only when it was tested immediately after onset, while the flickering cue had been presented already for a number of repetitions. In Experiment 2, the delayed static cue was superior when tested immediately after onset. In both cases, if the flickering cue's effectiveness had not decayed, it should have been superior for all CLTs.

The present experiments show that a flickering cue can maintain its cueing effectiveness for quite some time. This seems to contradict the results of Nakayama and Mackeben (1989) who argued that the effectiveness of a cue cannot be prolonged by flickering it. In fact, they stated that 'the repetition of local sensory transients is not able to maintain attention at the cued locus' (pp. 1640). They concluded this because the effectiveness of the cued location decreased over time even if flicker was present. It is important to note that we too find a decrement of flicker efficiency over time, so that in this sense our results and theirs are congruent. What we have done, which they have not, is to compare directly the effectiveness of a flickering cue with that of a non-flickering cue using the split priming motion induction paradigm. This enabled us to confirm the Nakayama and Mackeben (1989) results that the effectiveness of a flickering cue decays over time, but it also permitted us to demonstrate that flickering the cue maintains the effectiveness of this cue at a higher level than in the non-flickering cue condition. These results are typified by the functions presented in the bottom of Fig. 7 where the decay function of effectiveness for a non-flickering cue shows a steeper slope than that for a flickering cue. It is clear from these data that if one was to compare a flickering and non-flickering cue at a CLT of 400 ms, for example, the flickering cue would be more effective in capturing attention.

4.2. Effects of flicker

In our experiments, we have attempted to use flicker in two ways to influence cue effectiveness: by adapting an area to flicker before the presentation of the cue (Experiment 1) and by using flickering cues (Experiments 2–4). These two manipulations can also be considered to be equivalent to a certain extent. Flickering a cue is the same as adapting this area to flicker. The last onset of the cue before the presentation of the test bar is equivalent to the onset of a cue after flicker adaptation of the area. From Experiment 1, we would therefore expect that the effectiveness of that particular cue is reduced as compared to a cue appearing at the unadapted location. If tested immediately after onset of the second cue, the nature of the second cue (flickering or static) should not matter. Both should be dominant over the first cue to the same extent. This was not the case in Experiment 4. This means either that we did not test early enough, since the earliest test bar appeared after a delay (CLT) of 225 ms, which corresponds to 2.5 cycles of flicker. This delay would affect the static cue much more than the flickering cue. Alternatively it could also be that adapting an area that is substantially larger than the subsequent cue presents a somewhat different situation in which stimulus identity is not preserved [flickering object (adaptation area) plus onset of a new stimulus (cue) vs. many stimulus onsets of the same stimulus (flickering cue)]. This was tested in Experiment 5. The fact that motion in the test bar was seen away from the previously large flickering area shows us that the large adapting flicker stimulus, like that used in Experiment 1, does not have the same properties as the flickering cues used in Experiments 2–4 and supports the notion that not preserving stimulus identity, as in the former case, does have an additional effect. In other words, even if exactly the same cues are presented to the left and right of the bar, each on an area which was previously flicker-adapted for the same amount of time, the one which is presented on the side where the large flickering adaptation area had been, takes on a novelty characteristic which also generates an attentional capture.

4.3. Concluding remarks

Objects that appear suddenly in our field of vision capture our attention for at least two reasons: Fast transient activity of the sudden onset leads to a perceptual facilitation of the stimulated location, resulting in attentional selection. The fact that the object is new gives its location additional saliency which will also lead to attentional selection.

Acknowledgements

This research was supported by grants from NSERC and FCAR to MvG and JF. We would like to thank Yen Vo for help in data collection and Peter April for the programming (Pixx software).

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